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NEW EXPERIMENTS WITH ANTIPROTONS

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Fermilab operates the world's most intense antiproton source. Recently proposed experiments can use those antiprotons either parasitically during Tevatron Collider running or after the Tevatron Collider finishes in about 2011. For example, the annihilation of 8 GeV antiprotons might make the world's most intense source of tagged D^0 mesons, and thus the best near-term opportunity to study charm mixing and search for new physics via its CP-violation signature. Other possible precision measurements include properties of the $X(3872)$ and the charmonium system. An experiment using a Penning trap and an atom interferometer could make the world's first measurement of the gravitational force on antimatter. These and other potential measurements using antiprotons could yield a broad physics program at Fermilab in the post-Tevatron era.

1. Introduction

Several intriguing questions, some involving CPT and Lorentz symmetry violation (the themes of this Meeting), can be studied with low- and medium-energy \bar{p} beams. These have motivated experiments at the CERN Antiproton Decelerator¹ and the planned \bar{P} ANDA experiment² at the Facility for Antiproton and Ion Research; as described below, such experiments are now proposed at Fermilab as well.^{3,4} 'Medium-energy' questions include new-physics searches in charm mixing and CP violation (CPV), hyperon decay, and the X , Y , and Z states, as well as antihydrogen CPT tests; at low energy, the gravitational force on antihydrogen can be measured.

Table 1 compares current and future antiproton sources. The highest-intensity antiproton source is at Fermilab. Having served $\bar{p}p$ fixed-target experiments including E760 and E835, it is now solely dedicated to the Tevatron Collider, but could once again support dedicated antiproton experiments after completion of the Tevatron program, currently planned for 2011 (although 2014 is a possibility under discussion).

Table 1. Antiproton energies and intensities at existing and future facilities.

Facility	\bar{p} K.E. (GeV)	Stacking:		Operation:	
		Rate ($10^{10}/\text{hr}$)	D.F.	Hrs/yr	$10^{13} \bar{p}/\text{yr}$
CERN AD	0.005, 0.047	—	—	3800	0.4
Fermilab Accumulator:					
now	8	20	90%	5550	100
proposed	$\approx 3.5\text{--}8$	20	15%	5550	17
with new ring	2–20?	20	90%	5550	100
FAIR ($\gtrsim 2018$)	2–15	3.5	90%	2780*	9

* The lower number of operating hours at FAIR arises from medium-energy antiproton operation having to share time with other programs.

2. Proposed antiproton experiments at Fermilab

2.1. Medium-energy \bar{p} -annihilation experiment

A very capable and cost-effective experiment can be mounted by adding a magnetic spectrometer to the E760 lead-glass calorimeter,⁵ using an available BESS solenoid,⁶ fine-pitch scintillating fibers (SciFi), the DØ SciFi readout system,⁷ and hadron ID via fast timing.⁸ This could produce world-leading measurements of charm mixing and the other effects mentioned above, provided the relevant cross sections are of the expected magnitude.

2.1.1. Charm mixing and CP violation

After a >20 -year search, D^0 mixing is now established at $>10\sigma$.⁹ While the $\approx 1\%$ mixing rate may indicate a Standard-Model origin,¹⁰ a significant new-physics contribution (signaled by CPV) is not ruled out.^{11–13} Since new physics can produce differing effects in the up- and down-type quark sectors,^{11,13} such studies are important not only with s and b hadrons, but also with charm—the only up-type meson that can mix.

Although unmeasured, somewhat above threshold ($\sqrt{s} \gtrsim 4 \text{ GeV}$) many expect $\sim \mu\text{b } \bar{p}N \rightarrow \text{open-charm production}$.^{14–16} E.g., using Eq. (5) of Ref. 17, we obtain $1.3 \mu\text{b}$ for the $D^{*0}\bar{D}^0$ final state. At $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, this is $\sim 5 \times 10^9$ events/year. Target- A dependence¹⁸ can enhance statistics by $\sim A^{1/3}$, giving a much larger sample than the B factories' 10^9 events. A wire or pellet target, limiting primary vertices to $\sim 10 \mu\text{m}$ in z , can make the D^0 decay distance resolvable. The low charged-particle multiplicity ($\langle n_{ch} \rangle \approx 2$) at this energy may allow clean samples with the application of only modest vertex cuts, hence high efficiency. Medium-energy $\bar{p}N$ interactions may thus be the optimal way to search for charm CPV.

Preliminary simulation and background studies imply a $D^{*\pm} \rightarrow D^0 \pi^\pm$

signal-to-background ratio of ~ 10 -to-1 before vertex cuts. With $150\ \mu\text{m}$ resolution in z , > 100 -to-1 signal-to-background seems possible with efficiency $\gtrsim 10\%$. Thus we can expect to reconstruct $\sim 3 \times 10^7$ tagged $D^0 \rightarrow K^-\pi^+$ events per year, compared with some 1.2×10^6 events in $0.54\ \text{fb}^{-1}$ at Belle.¹⁹

2.1.2. Hyperon CP violation and rare decays

The HyperCP Experiment²⁰ detected unexpected possible signals at the $\gtrsim 2\sigma$ level for new physics in the rare decay²¹ $\Sigma^+ \rightarrow p\mu^+\mu^-$ and the $\Xi^- \rightarrow \Lambda\pi^-$ CP asymmetry:²² $A_{\Xi\Lambda} = [-6.0 \pm 2.1(\text{stat}) \pm 2.0(\text{syst})] \times 10^{-4}$. Since the $\bar{p}p \rightarrow \Omega^-\bar{\Omega}^+$ threshold lies in the same region as the open-charm threshold, the proposed experiment can test these observations using $\Omega^- \rightarrow \Xi^-\mu^+\mu^-$ decays and potential $(\bar{\Omega})^\mp$ CPV (signaled by small $\Omega^-\bar{\Omega}$ decay-width differences in $(\bar{\Lambda})K^\mp$ or $(\bar{\Xi})^0\pi^\mp$ final states²³).

Extrapolation from $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ and $\Xi^-\bar{\Xi}^+$ implies $\sigma(\bar{p}p \rightarrow \Omega^-\bar{\Omega}^+) \approx 60\ \text{nb}$ just above threshold, or $\sim 10^8$ events/year. What's more, the measured $\approx 1\ \text{mb}$ cross section²⁴ for associated hyperon production means $\sim 10^{12}$ events/year, which could directly confront the HyperCP evidence (at 2.4σ significance) for a possible new particle of mass $214.3\ \text{MeV}/c^2$ in the three observed $\Sigma^+ \rightarrow p\mu^+\mu^-$ events.²¹ Further in the future, the dedicated \bar{p} storage ring of Table 1 might decelerate antiprotons to the $\Lambda\bar{\Lambda}$, $\Sigma^+\bar{\Sigma}^-$, and $\Xi^-\bar{\Xi}^+$ thresholds, for a comprehensive program testing hyperon CPV.

2.1.3. Precision measurements in the charmonium region

E760 and E835 made the world's most precise ($\lesssim 100\ \text{keV}$) measurements of charmonium masses and widths,^{25,26} thanks to the precisely known collision energy of the stochastically cooled \bar{p} beam and the H_2 -jet target. Significant charmonium-related questions remain, most notably the nature of the mysterious $X(3872)$ state²⁷ and improved measurements of the h_c and η'_c .²⁸ The width of the X may well be $\ll 1\ \text{MeV}$.²⁹ The unique $\bar{p}p$ precision is what is needed to establish whether the $X(3872)$ is a $D^{*0}\bar{D}^0$ molecule.³⁰

The $\bar{p}p \rightarrow X(3872)$ formation cross section may be similar to that of the χ_c states.^{17,31} The E760 χ_{c1} and χ_{c2} detection rates of $1\ \text{event/nb}^{-1}$ at the mass peak,³² along with the lower limit $\mathcal{B}[X(3872) \rightarrow \pi^+\pi^-J/\psi] > 0.042$ at 90% C.L.,³³ imply that at the peak of the $X(3872)$, about 500 events/day can be observed. (Although CDF and DØ could also amass $\sim 10^4$ $X(3872)$ decays, backgrounds and energy resolution limit their incisiveness.) Large samples will also be obtained in other modes besides $\pi^+\pi^-J/\psi$, increasing the statistics and improving knowledge of $X(3872)$ branching ratios.

The above may be an under- or an overestimate, perhaps by as much as an order of magnitude. Nevertheless, it appears that a new experiment at the Antiproton Accumulator could obtain the world's largest clean samples of $X(3872)$, in perhaps as little as a month of running. The high statistics, event cleanliness, and unique precision available in the $\bar{p}p$ formation technique could enable the world's smallest systematics. Such an experiment could thus provide a definitive test of the nature of the $X(3872)$.

2.2. Antihydrogen experiments

2.2.1. In-flight CPT tests

Production of antihydrogen in flight³⁴ may offer a way around some of the difficulties encountered in the CERN trapping experiments. Methods to measure the antihydrogen Lamb shift and fine structure have been proposed.³⁵ Progress towards this goal may be compatible with normal Tevatron Collider operations (a possibility currently under investigation), and the program could continue into the post-Tevatron era.

2.2.2. Antimatter Gravity Experiment

While General Relativity predicts identical gravitational forces on matter and antimatter, a direct experimental test has yet to be made.³⁶ Quantum gravity can include non-tensor forces that cancel for matter-matter interactions but add for matter-antimatter ones. Possible fifth forces, non- $1/r^2$ dependence, and Lorentz violation have also been discussed.³⁷ The acceleration of antimatter (\bar{g}) in the earth's gravitational field is sensitive to these effects. Such a measurement for antihydrogen ($\bar{\text{H}}$) has only recently become feasible and is now approved at the AD³⁸ and proposed at Fermilab.³ The Fermilab proposal³ seeks to form a slow (≈ 1 km/s) $\bar{\text{H}}$ beam in a Penning trap and pass it through an atom interferometer, using either material gratings (giving $\delta g/g \sim 10^{-4}$) or laser techniques³⁹ ($\delta g/g \sim 10^{-9}$). Fermilab's high \bar{p} flux means that even an inefficient ($\sim 10^{-4}$) deceleration approach gives enough antiprotons for competitive measurements. Deceleration ideas start with the Main Injector, probably useable down to ≈ 400 MeV, followed by an 'antiproton refrigerator,'⁴⁰ reverse linac, or small synchrotron.³

3. Outlook

When the Tevatron Collider program completes, new and unique measurements can be made at the Fermilab Antiproton Source.^{41,42} Such a program can substantially broaden the clientele and appeal of US particle physics.

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